Crop Nutrition: Measure to Manage

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Abstract:

Crop nutrition requires urgent transformation to reduce costs, pollution, climate change, and to improve and secure food production. Amazingly, very few professional farmers in the 21st century check their crops' nutritional performance! So farmers, advisors, their industry and their governments do not know what nutrient management errors are costing, or how to reduce them. This paper argues, and provides strong evidence from the Yield Enhancement Network (or 'YEN'), that the modern farming industry can and should check how well it is managing its biggest input: nutrients. This must be done by analysing what is harvested from every field. Nutrient harvests (kg/ha) vary hugely; they cannot be guessed, but they are easy and accurate to measure. Nutrient concentrations (%DM) at harvest show whether crops captured insufficient, adequate or excess of each nutrient. Without measures at harvest, nutrient management is guesswork and this prevents improvement. New UK evidence shows that over 80% of crops on even the best farms show a deficiency of at least one nutrient, >50% show more than one, and 20% of crops receive excess N. The most common deficiency is of phosphorus, but nitrogen, magnesium and sulphur deficiencies are common. This is despite phosphorus availability in the soil being deemed adequate on 80% of arable fields. Nutrient harvests are suggesting that uptake processes are inadequate in many fields, perhaps due to poor rooting or topsoil dryness following nutrient applications.

Most variation in crop performance relates to the farm, rather than to the season, the region, the variety, or the soil type. So fastest improvement can be achieved by farms comparing themselves with each other and learning from the best performers. The YEN enables farms to do this through 'benchmarking'.

In some instances it may prove worthwhile for farms to test proposed solutions themselves before adopting these farm-wide. Greatest confidence can be derived from such tests by also conducting them in partnership with other farms.

Keywords: Essential nutrients; critical thresholds; grain analysis; nutrient capture; offtake; nutrient harvest; nutrient balance; nutrient partitioning; on-farm experimentation.

Introduction:

Crop nutrients have new importance due to increases in both their economic (Fig.1) and environmental costs. Attitudes to crop nutrient management must therefore change with some urgency, if (i) farms are to sustain their profitability, (ii) Europe is to sustain and secure its food production, but also (iii) pollute air and water less, and (iv) cause less climate change. Indeed farms may be required to show that they are supporting the aims of the EU's Green Deal by demonstrating 20% less fertiliser use and 50% less loss of nutrients. But how can they do this?

Current nutrient management on NW European farms is rule-based; farms make very few measurements themselves. They generally measure soil pH and a few soil nutrients every 3-5 years but then they estimate other soil nutrient availabilities, including of nitrogen (N), and all crop nutrient demands and removals by relying on average values, or on decisions made elsewhere in previous seasons. Although farms generally manage crops field-by-field, taking into account soil type and rotation, they often only measure the total produce that they sell, rather than the produce that they harvest from each field, and the only nutrient measured is N.

To manage any other production system, it is necessary to know quantities of inputs and outputs (both boughten and free), and quantities stored, in order to gauge how well the system is performing, and to work out how to improve this; confident management depends on good measurements. Because prices fluctuate, essential measurements for managing production systems must be physical as well as financial. They must record intake, storage and use of primary inputs, and they must show ultimate outputs and losses (or inefficiencies) in manageable sub-processes.

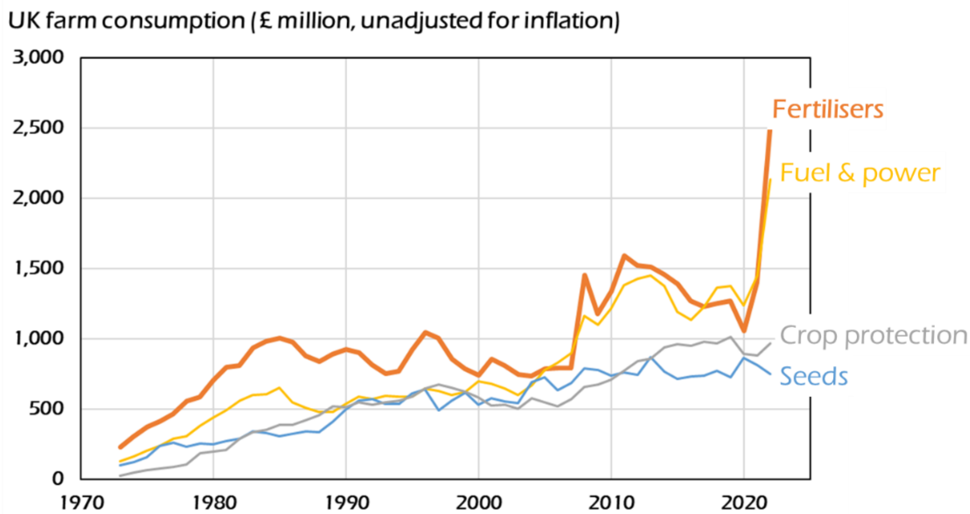


Fig.1: Trends since the 1970s in spending on inputs by UK farms, showing the dominance of fertilisers.

When existing approaches to monitoring crop production and nutrition are examined from this perspective, current monitoring practices seem decidedly inadequate. Whilst seed, agrochemical and nutrient inputs are commonly recorded field by field, records of outputs field-by-field are sparse, and measures of soil-stored nutrients are incomplete (only 3-4 of the 12 essential crop nutrients), imprecise and infrequent (every 3-5 years). Moreover soil measurements can only indicate nutrient *availability* rather than *crop capture* or *field exports*. To a scientist, this seems odd. Possibly the reason that farms do not make routine field records of their field outputs is that crop variation seems too large and uncontrollable to manage field-by-field.

Using data from the Yield Enhancement Network (or 'YEN'; Sylvester-Bradley & Kindred, 2014; Clarke *et al*., 2017; White *et al*., 2022) over the past decade, this paper explores the feasibility and value of farms measuring nutrient inputs and outputs field-by-field and year-by-year, as well as the final nutritional status of each crop. Our idea is that farms could thereby manage their nutritional practices better, test improvements and demonstrate proven progress.

The YEN Dataset:

The YEN was initiated in 2013 with ~30 farms competing to produce the greatest grain yield from a cereal crop at field-scale (>2 ha). As well as measuring grain yields, each farm recorded a range of explanatory metrics including nutrient inputs and soil nutrient levels. They also took crop samples from which yield components (heads/m^2, grains/head, weight/grain and harvest index), and quantities of nutrients harvested were determined. The YEN has continued annually since 2013 and has grown to engage hundreds of farms and to explore production of oilseeds and pulses, as well as cereals. About 90% of YEN crops have been entered from UK farms; the others have been from Ireland or mainland Europe (only two from France!) and, since 2016, YENs have been initiated in Atlantic Canada and the Great Lakes' region, mainly Ontario & Michigan. About half of YEN grain yields have been independently validated in order to qualify for inclusion in competitions for the greatest yield. However, many crops have been entered yields without validation because the contributing farm then received a thorough report (~20-pages) which presented and benchmarked ~100 metrics designed to explain the yield achieved. These metrics include analyses of nutrient levels in soil, leaf, straw and grain. Explanatory metrics for grain yields have inevitably been incomplete; the proportions of grain yields until 2021 having associated soil, leaf, straw and grain analyses were 86%, 11%, 40% & 84%. Straw was only analysed for N content.

Data from European YEN crops have been collated into a database which, for this presentation, contained yields of ~2,000 wheat crops up to harvest 2021. These data have been processed and analysed to demonstrate how crop yields and nutrition of autumn-sown wheat crops vary, and then to explore the value of introducing farm-driven measurements to improve management of crop nutrition.

Nutritional Findings:

Crop yields on YEN fields vary hugely. Wheat yields in the YEN database average 10.0 t/ha but range from 2 to 18 t/ha and have a standard deviation of 2.1 t/ha. Grain nutrient concentrations also vary; N, phosphorus (P), potassium (K) and other macro-nutrients vary almost as much as grain yields. N, P & K all show a two-fold range (Fig.2) and most micro-nutrients vary even more.

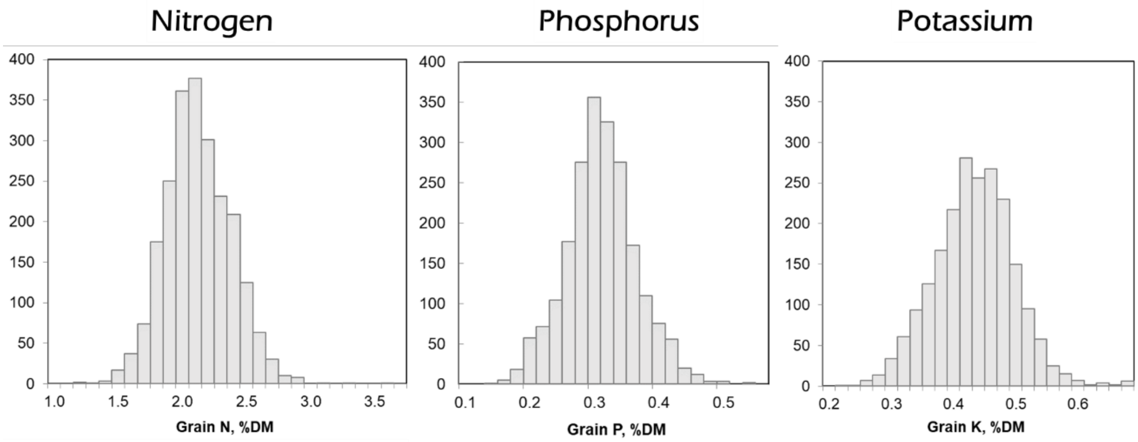


Fig.2: Frequencies of concentrations of N, P & K in grain harvested from ~1,400 wheat crops entered in the YEN, 2013-2021.

Although concentrations of most grain nutrients are negatively related to grain yields (often called 'yield dilution') YEN yields never explain more than a quarter of variation in grain nutrient concentrations, and grain P is positively related to yield, suggesting that greater crop capture of P may enhance grain yield.

Balances

Measured nutrient concentrations were commonly less than 'standard' grain nutrient concentrations assumed in UK fertiliser recommendations, so on average P & K applications calculated from measured grain concentrations cost less than applications using the standard values; the average financial saving exceeds the cost of grain analysis. Thus grain nutrient variation is such that standard assumptions are inadequate; indeed, standard assumptions have caused over-application of P & K on many farms for several decades!

Diagnosis of nutrient deficiencies (& excesses)

Distribution between grain and straw at harvest varies hugely between nutrients, but is fairly similar between crops (Fig. 3), with P being mostly held in grain but B being mostly held in straw. Thus grain P and N concentrations are highly representative of the success of crops in capturing P and N, whereas grain B is less useful in indicating total crop B capture.

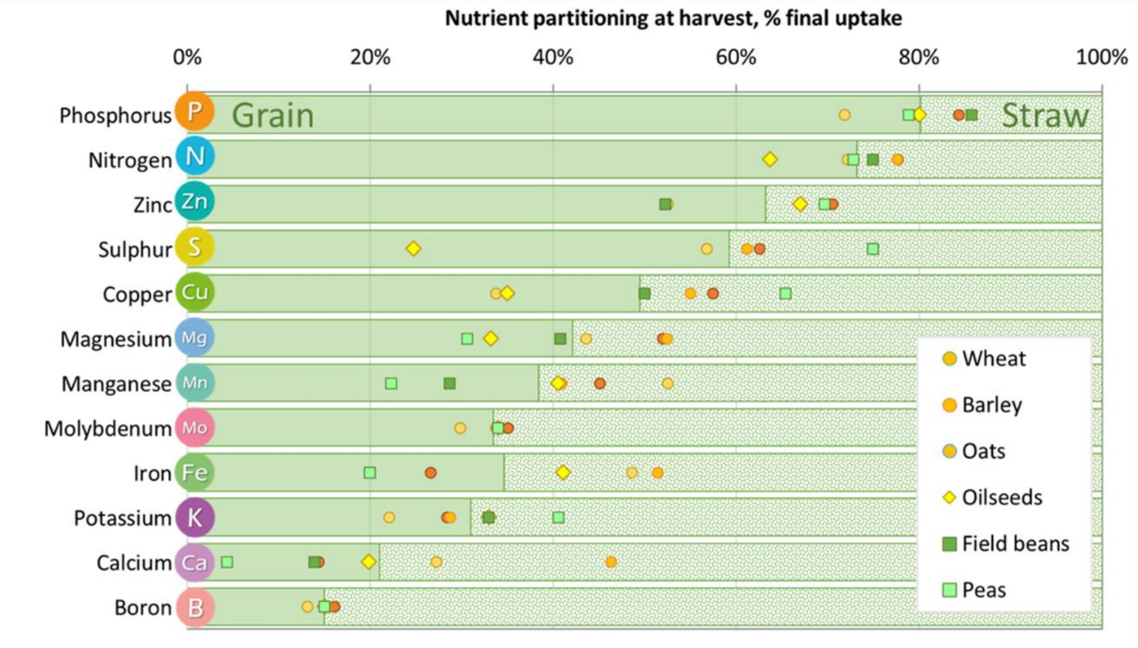
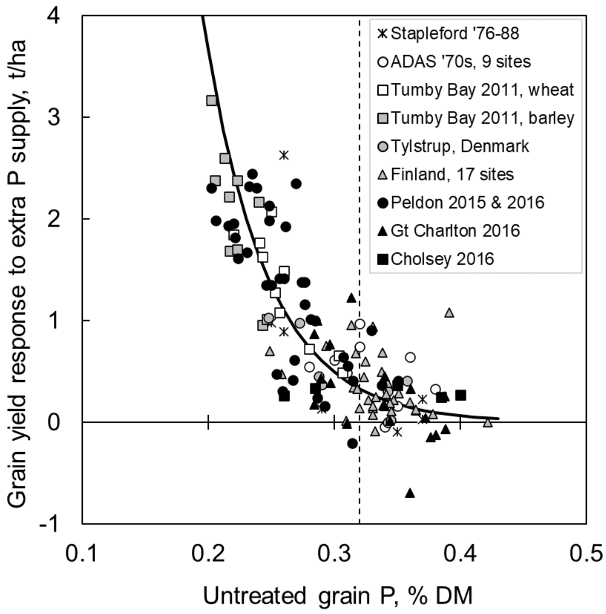


Fig. 3: Approximate distribution of all essential nutrients between grain and straw of arable crops at harvest. Grain analysis is much more indicative of total crop capture for P than for B.

Deficiencies occur when nutrient capture is insufficient to support growth. Maximum crop nutrient concentrations associated with deficiencies are defined as 'critical'; these can only be determined by experiment. Indeed, many experiments are required to build sufficient certainty that a nutrient concentration should be regarded as 'critical'. As an example, Fig. 4 shows how the critical value of 0.32%DM was derived for grain P in cereal crops. Our review of the literature on grain nutrient concentrations concluded that eight nutrients have critical values with adequate certainty for nutritional diagnosis (Table 1).

Fig. 4: Grain yield responses to additional P supply at multiple sites in the UK and Scandinavia since the 1970s (caused by phosphate applications in previous years) according to grain P concentrations without additional P. The vertical dotted line shows the grain P concentration of 0.32 %DM deemed to be 'critical' (from Sylvester-Bradley et al., 2019b).



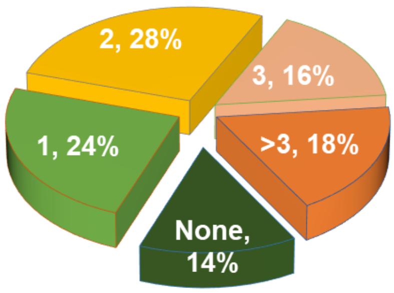
The frequencies of individual deficiencies are shown in Table 1. In addition to these, grain N (or protein) concentrations can be used to diagnose *excess* crop capture of N, after adjusting for known differences between cultivars. Excess capture usually arises from excess supply of N to the crop (Sylvester-Bradley & Clarke, 2009), perhaps due to over-optimistic yield expectation. Grain N values in the YEN database indicate that approximately 20% of wheat crops had N supplies at least 50 kg/ha in excess of their requirements, in addition to the 22% that were deficient.

Comparison of these critical values with nutrient concentrations in the YEN database suggests that more than 80% of YEN wheat crops were deficient in one nutrient, and more than 50% were deficient in more than one nutrient (Fig. 5). Thus grain analysis shows that nutritional errors, even on the best farms, are surprisingly common.

Table 1: Critical concentrations of eight of the 12 essential nutrients in wheat grain (Sylvester-Bradley et al., 2022) and proportions of ~1,700 YEN entries with less of each nutrient.

Nutrient	***Critical concentration (%DM or mg/kg DM)***	***Frequency of deficiencies in YEN***
Nitrogen, N	1.9 (feed) 2.1 (bread)	22%
Phosphorus, P	0.32	65%
Potassium, K	0.38	25%
Magnesium, Mg	0.08	27%
Sulphur, S	0.12	33%
Manganese, Mn, mg/kg DM	20	20%
Zinc, Zn, mg/kg DM	15	4%
Copper, Cu, mg/kg DM	3	18%

Fig. 5: Proportions of ~1,700 YEN wheat entries from 2013-2021 affected by different numbers of deficiencies (from None to >3) i.e. with grain nutrient concentrations less than the critical thresholds in Table 1.



Discussion:

At present the crop nutrition industry, especially farms, can be justifiably accused of 'not knowing what it is doing', in the sense that farms are responsible for distributing large quantities of expensive nutrients without ever measuring their fate, whether in the crops they grow and use or sell, or in emissions inadvertently leaking into their environment. Farms commonly measure nutrient inputs. Farms engaging in the YEN have shown that it is perfectly feasible to include grain sampling within their workplans, even at the busy time of harvest. Furthermore, analysis of the YEN Database shows that just by using less P & K fertiliser (to balance the *measured* offtakes), the average benefit significantly exceeds the cost to the farm of sampling, analysis and interpretation of results (about €60 per field). So all farms can measure nutrient harvests, with no need for extra skill or knowledge.

However, the challenge of persuading farms to do this is conceptual rather than technical. The industry's maxim of 'feed the soil to feed the crop' focusses primary attention on soil measurements. If the industry is to regard nutrient harvests as their most telling metric, and thereby reduce costs and pollution, their maxim must change to 'feed the crop, not the soil' (Withers *et al*., 2014).

High prices and insecurity of fertiliser supply resulting from Russia's war on Ukraine now provide drivers for changes in the industry's currently complacent approach to nutrient use. Experience with farms engaging in the YEN has shown that once nutrient harvests have been measured field by field, a farm's focus turns from soil supplies towards efficient crop capture.

Whilst P & K are the prime nutrients for which farms seek a balance between applications and removals, balances can prove useful for all nutrients. Even well intentioned farms may be unsure of the quantities of each nutrient that a crop captures so they may inadvertently make inappropriately small or large applications e.g. the mismatch of manganese supply and demand in Table 2. And for most other nutrients, including N, farms may be concerned about operating with positive or negative soil balances.

*Table 2: Example of how soil, leaf and grain analysis might enable estimation of crop capture and soil balance for all nutrients on an example field of triticale. *Manure nutrients were taken from standard assumptions, but are better estimated from lab. analysis, especially for N.*

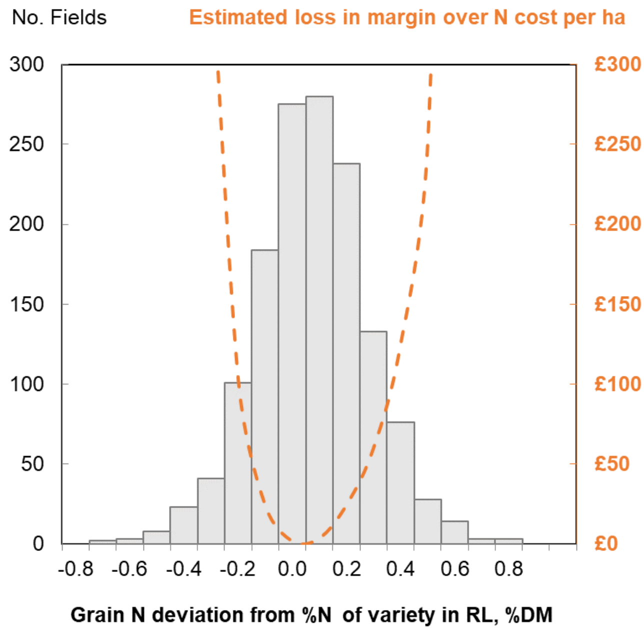
	Macro-Nutrients							Micro-Nutrients						
	units	N	P	K	Mg	S	Ca	*units*	Fe	Mn	Zn	Cu	B	Mo
Demand budget @ yield (t/ha) 6.5	*kg/ha*	135	20	90	15	15	15	*g/ha*	510	260	235	120	10	10
Soil Supply														
Soil analysis	*mg/l*	-	23	307	280	-	-	*mg/l*	-	-	-	-	-	-
Soil Index	*Index*	-	2+	3	5	-	-	*Index*	-	-	-	-	-	-
Total Nutrients Applied	*kg/ha*	156	0	0	1	57	0	*g/ha*	0	3,000	0	0	>0	0
In Organic Manures (totals*)	*kg/ha*	0	0	0	0	0	0	*g/ha*	0	0	0	0	0	0
In Fertilisers & Sprays	*kg/ha*	156	0	0	1	57	-	*Yes ?*	-	3,000	-	-	Yes	-
Crop Capture with yield (t/ha) of 7.5	*kg/ha*	189	50	121	19	39	13	*g/ha*	463	241	353	148	8	15
Demand difference from budget	*kg/ha*	+54	+30	+31	+4	+24	-2	*g/ha*	-48	-19	+118	+28	-2	+5
Leaf analysis at Growth Stage 31	*% DM*	3.63	0.38	2.12	0.14	0.37	0.76	*ppm*	116	67	21	6	8.6	1.5
Grain analysis	*% DM*	2.30	0.30	0.51	0.11	0.13	0.03	*ppm*	32	21	39	5	0.9	0.8
Harvest offtakes	*kg/ha*	168	20	66	9	12	8	*g/ha*	335	187	302	91	7	10
Soil Balance	*kg/ha*	-12	-20	-66	-9	45	-8	*g/ha*	-335	2,813	-302	-91	NA	-10
All values are for elements. For Oxides (e.g. P_2O_5) multiply by:		1.0	2.3	1.2	1.7	2.5	1.0		1.0	1.0	1.0	1.0	1.0	1.0

In addition, farms are seeing much larger benefits of diagnosing deficiencies (and excesses) of most nutrients, especially N and P. These are the most expensive nutrients and are responsible for the most concerning environmental impacts. Fig. 6 illustrates how deviations in grain N concentration from a variety's 'norm' relate to financial losses, whether from sub-optimal yield or excess fertiliser use. Assuming an average field size of 12 ha, the average cost of N & P errors by YEN farms has been estimated to be around €4,000 per field at 2022 prices, and to exceed €9,000 on 10% of fields (Sylvester-Bradley *et al*., 2022).

Crop yields in the YEN Database vary hugely. Analysis has revealed that the main associations are not with crop genetics, agronomic practices, soil characteristics or even years, but with the farms themselves and then with their fields (Sylvester-Bradley *et al*., 2019). This analysis suggests that, before they despair of uncontrollable seasonal effects, or concern themselves with varieties or responses to specific products, their principal focus should be on how their own performance, and that on their individual fields, differ from others. Although formal analysis of variation in YEN's grain nutrient concentrations is still incomplete, large farm-to-farm variation is plainly evident – some farms appear consistently generous whilst others appear consistently frugal – so it is likely that farms can most hastily enhance their nutritional performance by learning from each other, and particularly from the best farms, once these are identified.

Of course diagnosing deficiencies after harvest is much easier than anticipating them and making exactly optimal fertiliser decisions at sowing and during early crop growth. So we must consider how grain analyses should be interpreted and acted upon. Experience in the YEN has shown that incomplete knowledge of critical values (Table 1) and seasonal variation in grain concentrations can cause uncertainties. These can be countered by enabling all farms to benchmark their nutrient levels from each field against those from all other similar fields on other farms. Rather than diagnosing deficiencies, YEN reports suggest that nutrient concentrations exceeded by 75% of all other similar crops (grown in the same year) should be treated as 'of concern' to the farm, and that further checking is needed. Low nutrient concentrations may arise from any of many causes: low soil content, inadequate fertiliser applications, inefficient fertilisers or manures, slow soil mineralisation, low nutrient mobility due to soil dryness, poor rooting, root disease, or low crop demand. So many good observations are necessary to identify causes of poor nutrient capture. These include soil analysis; however, YEN data show that grain P or K concentrations do not relate well to soil concentrations.

Fig. 6: Frequency of deviations in grain N concentration from the national variety average (from AHDB RL trials) amongst ~1,400 wheat crops entered in the YEN from 2013 to 2021. The orange line showing estimated losses in margin above N cost (at 2022 fertiliser N prices) associated with these deviations in grain N%. (Sylvester-Bradley et al., 2022).



Measuring nutritional performance is only the first step in improving it. Farm nutrient harvests have revealed widespread crop nutrient deficiencies associated with inefficient recovery of applied and soil-derived nutrients. This has initiated farm-driven questioning of crop nutrition processes and prompted farm-sponsored testing of nutritional products and practices.

Low grain nutrient levels should initially prompt additional checking of soil and maybe leaf and straw levels in crops grown next year, or on other fields in the same year. Usually a diagnosis must prompt a correction to management strategy. If this correction is uncertain or expensive, it may be worth introducing on-farm tests. With the advent of yield mapping harvesters, on-farm testing is become significantly easier, and farms are beginning to undertake their own trials (Lacoste *et al.*, 2022). However, to answer uncertain nutritional questions farms must invest considerable care in designing any tests (Marchant *et al*., 2018; Roques *et al*., 2022); for example, they should also choose between testing the omission or addition of a new treatment; we call such tests 'practice omission patches' (POPs) or 'practice addition patches' (PAPs). Experience with on-farm testing shows that, by using appropriate statistical analyses that recognise inherent spatial variation, confidence levels in on-farm tests can exceed those that normally arise from small-plot experiments conducted by full-time researchers.

Given the importance of measuring nutrients in order to manage them better, a new EU-funded project has been initiated called NUTRICHECK NET. The project is being managed by Arvalis in France, and has formed 27 Crop Nutrition Clubs in nine countries across Europe. The intention is, by the end of 2025, to identify the means of monitoring crop nutrition that European farms find most user-friendly, accurate and helpful.

Conclusions:

- It is amazing that professional farmers in the 21st century do not check their crops' final nutrition.
- Analyses of nutrient harvests in the YEN Database show that nutrient management errors are costing many farms thousands of Euros per field. Yet farmers, advisors, their industry and their governments do not know this!
- Any farm can check how well it is managing nutrients just by analysing what it harvests from every field. The trouble and expense of crop sampling and analysis at harvest is a 'no brainer'!
- Nutrient harvests (kg/ha) vary hugely; they cannot be guessed, but they are easy and accurate to measure. Nutrient concentrations (%DM) show whether a crop captured insufficient, adequate or excess of each nutrient.
- UK evidence suggests that over 80% of crops on even the best farms show a deficiency of at least one nutrient, >50% show more than one, and 20% of crops have received excess N. The most common deficiency is of phosphorus, but nitrogen, magnesium and sulphur deficiencies are common. This is despite phosphorus availability in the soil being deemed adequate on 80% of arable fields.
- Nutrient harvests show that uptake processes on many fields are inadequate, perhaps due to poor rooting or to topsoil dryness after nutrient application.
- Knowledge of nutrient harvests should lead to inter-farm comparisons, identifying practices associated with best crop capture, and then on-farm testing of improvements to management of crop nutrition.
- A new EU-funded project called NUTRI-CHECK NET is seeking transformation of crop nutrition across Europe by forming and coordinating regional 'crop nutrition clubs' and networks to drive the technical and conceptual changes that are so essential to effecting progress in crop nutrition.

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